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Title page

Unilateral above-knee amputees achieve symmetric mediolateral ground reaction impulse in walking using an asymmetric gait strategy

Submitted as a short communication

by

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Abstract

The ability to sustain steady straight-ahead walking is one goal of gait rehabilitation for individuals with unilateral above-knee (UAK) amputation. Despite the morphological and musculoskeletal asymmetry resulting from unilateral limb loss, the mediolateral ground-reaction-impulse (GRI) should be counterbalanced between the affected and unaffected limbs during straight-ahead walking. Therefore, we investigated the strategies of mediolateral ground-reaction-force (GRF) generation adopted by UAK prosthesis users walking along a straight path. GRFs of 15 participants with UAK amputation were measured during straight-ahead walking. Then, the mediolateral GRI, stance time, and mean mediolateral GRF during the stance phase of the affected and unaffected limbs were compared. To better understand the GRF generation strategy, statistical-parametric-mapping (SPM) was applied to assess the phase-dependent difference of the mediolateral GRFs between two limbs. The results showed that UAK prosthesis users can achieve symmetric mediolateral GRI during straight-ahead walking by adopting an asymmetric gait strategy: shorter stance time and higher mean mediolateral GRF over the stance phase for the affected than for the unaffected limb. In addition, the analysis using SPM revealed that the affected limb generates a higher mean medial GRF component than the unaffected limb, especially during the single-support phase. Thus, a higher medial GRF during the single-support phase of the affected limb may allow UAK prosthesis users to achieve mediolateral GRI that are similar to those of the unaffected limb. Further insights on these mechanics may serve as guidelines on the improved design of prosthetic devices and the rehabilitation needs of UAK prosthesis users.

Keywords: Amputee locomotion, above-knee amputee, gait, straight-ahead walking, ground reaction impulse

1. Introduction

The ability to sustain steady straight-ahead walking is important for daily ambulation and is one goal of gait rehabilitation for individuals with unilateral above-knee (UAK) amputation. In fact, UAK prosthesis users are required to achieve mediolateral gait symmetry during straight-ahead walking despite the morphological and musculoskeletal asymmetry resulting from unilateral limb loss (Kaufman et al., 2012; Schaarschmidt et al., 2012). Although previous studies have focused on evaluating the gait characteristics and functional performance in UAK prosthesis users during straight-ahead walking (Frossard et al., 2003; Lee et al., 2007; Dumas et al., 2017; Jarvis et al., 2017; Weinert-Aplin et al., 2017; Carse et al., 2020), the fundamental biomechanics underlying straight-ahead walking remains to be suitably characterized for these prothesis users.

Forward ambulation of individuals with UAK amputation is achieved by modulating the mediolateral components of the ground reaction impulse (GRI) in both limbs to generate sinusoidal oscillation of the body center of mass (COM) in the horizontal plane (Hof et al., 2007; Weinert-Aplin et al., 2017; Carse et al., 2020). Therefore, to sustain straight-ahead walking, the net mediolateral displacement of the COM should be zero at each cyclic stride. According to the physical principle (Hibbeler, 2012), the corresponding net mediolateral momentum should be close to zero. In addition, as the mediolateral GRI directly influences the mediolateral momentum of the COM (Orendurff et al., 2006; Glaister et al., 2008), the former should be counterbalanced between the affected and unaffected limbs of UAK prosthesis users during straight-ahead walking to maintain the net zero momentum.

This study aimed to investigate the mediolateral GRF generation strategies adopted by UAK prosthesis users for sustaining straight-ahead walking. The prosthetic limb must be engaged to generate mediolateral GRI equivalent to those of the unaffected limb for forward ambulation in a straight path. Since the impulse is a function of time and force, we can identify the separate contributions of the mediolateral GRF duration and magnitude in both limbs to achieve a symmetric impulse under asymmetric limb loss. As the stance time of the affected limb has been reported to be shorter than that of the unaffected limb (Nolan et al., 2003; Hof et al., 2007; Schaarschmidt et al., 2012; Mahon et al., 2017), we hypothesize that the mean mediolateral GRF of the affected limb is higher than that of the unaffected limb. UAK prosthesis users demonstrated a unimodal mediolateral GRF-time curve in the affected limb, while a bimodal in the unaffected limb in a previous study (Zhang et al., 2019). Thus, we hypothesize that the affected limb generates higher mean mediolateral GRF than the unaffected limb, especially at midstance. Our investigation of the mediolateral GRF generation strategies to achieve symmetric GRI aims to enhance the understanding of the mechanisms adopted by UAK prosthesis users to sustain straight-ahead walking.

2. Methods

2.1. Participants

Fifteen individuals (10 men and 5 women) with UAK amputation (including 2 individuals with knee disarticulation) participated in this study (Table 1). All the participants were accustomed to their habitual prostheses, could walk independently without walking aids, and were categorized as US Medicare Classification Functional

Level K4 (US Health Care Financing Administration, 2001; Borrenpohl et al., 2016). Written informed consent was obtained from all 15 participants as well as the guardian of the participant who had an appointed guardian before the study began. The study protocol was approved by the local ethics committee and conformed to the Declaration of Helsinki.

2.2. Experimental procedure and data collection

Before performing the walking task, the participants were provided accommodation time to practice walking in the laboratory while maintaining their natural gait. Subsequently, the participants completed repeated trials of straight-ahead level walking at a comfortable, self-selected pace along a 10 m walkway. The GRF was measured using nine walkway-embedded force plates (BP400600-1000PT and BP400600-2000PT, AMTI, Watertown, MA, USA) at a sampling rate of 2000 Hz. All of the participants were provided adequate rest breaks for as long as necessary between trials to minimize fatigue bias.

2.3. Data analysis and reduction

The GRF data from five clean force-plate strikes (i.e., strikes with the entire foot laying within the plate) were analyzed for both the affected and unaffected limbs of each participant (Glaister et al., 2008). The collected GRF data were processed using a fourth-order Butterworth filter with zero lag and a cutoff frequency of 50 Hz (Hisano et al., 2020). The timings of initial contact and toe-off were defined by vertical GRFs above and below 16 N, respectively (Makimoto et al., 2017). The stance time was calculated as the period from initial contact to toe-off of the ipsilateral limb during stance. The mediolateral GRI, stance time, and mean mediolateral GRF during the stance phase were calculated per step for both limbs. The medial (positive) and lateral (negative) values of the GRF and GRI were defined as those acting to push the body towards and away from the contralateral limb, respectively. The data processing and analyses were conducted on the Visual 3D software (C-Motion, Germantown, MD, USA). The averaged GRI, mean GRF, stance time and GRF time series across the five trials were served as the representative values per participant. Based on the average within-subject standard deviation of GRI, mean GRF and stance time (See the supplementary material), taking an average across five steps was appropriate for the following statistical analysis.

2.4. Statistical analysis

We confirmed violation of the normality assumption by applying the Shapiro–Wilk test. Hence, the Wilcoxon signed-rank test was used to assess the main effect of the limb side (affected versus unaffected) for the three dependent variables with critical α of 0.05. The statistical analyses were conducted on the IBM SPSS 22.0 statistical software (IBM, Armonk, NY, USA).

To further analyze the GRF generation strategy, we evaluated the temporal differences in the mediolateral GRF profiles between the limbs. Specifically, statistical parametric mapping (SPM; Friston et al., 2007) was conducted to assess the phase-dependent difference of the averaged mediolateral GRFs between the two limbs over time by using package spm1d v0.3 (www.spmid.org) implemented in Python 2.7. The averaged mediolateral GRF over time was normalized from 0 to 100% of the stance phase. A statistical parametric map (SPM{t}) was created by calculating the conventional tstatistic at each point of the stance phase (Pataky et al., 2010, Pataky et al., 2012). Afterwards, Random Field Theory was used to determine the critical threshold of that only 5% ($\alpha = 0.05$) of equally smooth random data are expected to exceed, which allows independent control of Type I errors when testing correlated field data (Adler and Taylor, 2007). If the temporal SPM value at a node exceeded this critical threshold, the mediolateral GRF was considered to differ significantly between the two limbs at that node.

3. Results

The results of the mediolateral GRF variables for both limbs are shown in Fig. 1. No significant difference was observed in the net mediolateral GRI between the affected and unaffected limbs ($z = -0.625$, $p = 0.532$). In contrast, the stance time of the affected limb was significantly shorter than that of the unaffected limb ($z = -3.436$, $p = 0.001$), and the mean mediolateral GRF of the affected limb was significantly higher than that of the unaffected limb ($z = -2.331$, $p = 0.019$).

The mean mediolateral GRF curves of the affected and unaffected limbs and the results of the SPM are shown in Fig. 2. The SPM revealed that the affected limb generates a higher medial GRF component than the unaffected limb (Fig. 2B), especially during the single-support phase (40–63% of the stance phase), because the affected limb did not exhibit the double-peak profile to the extent of the unaffected limb profile (Fig. 2A).

4. Discussion and conclusion

We aimed to investigate the mediolateral GRF generation strategies adopted by UAK prosthesis users during straight-ahead walking. No significant differences were found in the mediolateral GRI between the two limbs (Fig. 1A), suggesting that UAK prosthesis users can sustain bilaterally symmetric mediolateral GRI throughout straight-ahead walking. The stance time of the affected limb was significantly shorter than that of the unaffected limb (Fig. 1B), being consistent with the findings of other studies. The affected limb is at risk of prosthetic knee buckling due to the lack of active control of this joint, which would generate a sudden loss of postural support when bearing weight (Felson et al., 2007). Given the possibility of prosthetic knee buckling during the stance phase of the affected limb (Lusardi et al., 2013; Hisano et al., 2020), the time of weight-bearing is usually minimized to reduce the likelihood of a fall. Therefore, short stance times may reflect a lack of confidence when transitioning the body over the prosthetic limb, thus indicating a cautious gait strategy.

Our results support the hypothesis of the mean mediolateral GRF being significantly higher in the affected limb than in the unaffected limb (Fig. 1C). Further, the SPM analysis revealed a significantly higher medial GRF in the affected limb than in the unaffected limb in 40–63% of the stance phase (Figs. 2A, B). These results may correspond to a reduced lateral GRF peak during the single-support phase of gait and lack of the double-peak in the medial GRF profile from the affected limb. Previous studies found similar differences between the affected and unaffected limbs (Soares et al., 2016; Zhang et al., 2019). These characteristics are possibly related to COM acceleration, which represents the effect of GRF generation. In 40–63% of the stance phase of the unaffected limb from passive prosthetic knee users, the soleus, gastrocnemius, and vasti are important contributors to lateral COM accelerations (Harandi et al., 2012). After UAK amputation, prosthesis users lose much of their function in the affected limb and rely on the intact hip and trunk musculature to generate forces and facilitate forward ambulation (Lusardi et al., 2013), possibly reducing the lateral GRF peak. On the other hand, during the corresponding phase of the affected limb, the gluteus medius, which is an important contributor to medial COM accelerations (Harandi et al., 2020), remains available and functional on the affected limbs of UAK prosthesis users. Therefore, the affected limb function combined with trunk dynamics can, in principle, compensate for the shorter stance time by generating higher average mediolateral GRFs during stance when compared to the unaffected limb to achieve a symmetric mediolateral GRI and sustain straight-ahead walking.

Nevertheless, there is limited evidence on the feasibility of excessive trunk motion being used for compensation to facilitate forward ambulation in lower-limb prosthesis users (Major et al., 2013; Brandt et al., 2019). Further, a previous study reported the direct correlation between mediolateral GRF and step width for both bilateral below-knee prosthesis users and able-bodied people (Major et al., 2013). Given the asymmetry in mediolateral GRF magnitude in UAK prosthesis users, this difference might be achieved by positioning the affected limb more lateral to the body than is done with the unaffected limb. However, no significant difference was observed in the mediolateral distance of each foot from the body COM over the stance phase, at peak medial GRF, and at initial contact (See the supplementary material). These results indicate that some UAK prosthesis users in our study might have achieved the asymmetric mediolateral GRF by asymmetric foot positioning strategies from the body COM, but others might not. Therefore, the relationships between kinematics and mediolateral GRF in prosthetic gait requires further investigation to provide a mechanical explanation for the observed characterization of GRF patterns in UAK prosthesis users. Moreover, prosthetic foot and knee systems that address mediolateral GRF generation may enable UAK prosthesis users to sustain straight-ahead walking. Thus, the relationship between prosthetic design and mediolateral GRFs during straight-ahead walking should also be explored in future work.

A limitation in this study is that walking speeds, which might affect the mediolateral GRF magnitude, was not controlled among individuals. Previous studies demonstrated the mediolateral GRF magnitude varies across a range of walking speeds (John et al., 2012: 0.54, 0.75, 1.15 and 1.56 m/s in able-bodied people; Silverman et al., 2011; 0.6, 0.9, 1.2 and 1.5 m/s in below-knee prosthesis users). However, variation of walking speeds among/within individuals in the present study is negligibly small when compared to the effect of the limb difference (See the supplementary material). An additional limitation of this study is associated with the activity level of the participants. We recruited participants with functional level K4, who are capable of exceeding basic ambulation skills (Gailey et al., 2002), and they show some different gait characteristics compared to UAK prosthesis users with functional level K3 (Sions et al., 2018). Also, our participants were relatively younger (33 years old on average) than those in the previous study which reviewed 12 articles regarding lower-limb prosthesis users with an average age of over 56 years old (Hunter et al., 2017). In addition, due to the relatively small number of participants with infection etiology, we could not perform subpopulation analysis based on the etiologic classification. Such demographic differences may affect the mediolateral GRF magnitudes and may limit the generalization of our findings.

Overall, we found that UAK prosthesis users achieve bilaterally symmetric mediolateral GRI during straight-ahead walking by adopting an asymmetric GRF generation strategy: reduced stance time and higher average mediolateral GRF in the affected limb. The higher medial GRF generation during the single-support phase in the affected limb may be the primary means to achieve mediolateral GRI similar to those of the unaffected limb. These and further insights on these mechanics may serve as guidelines on the improved design of prosthetic devices and the rehabilitation needs of UAK prosthesis users.

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Conflict of interest statement

None of the authors have any conflicts of interest regarding this study.

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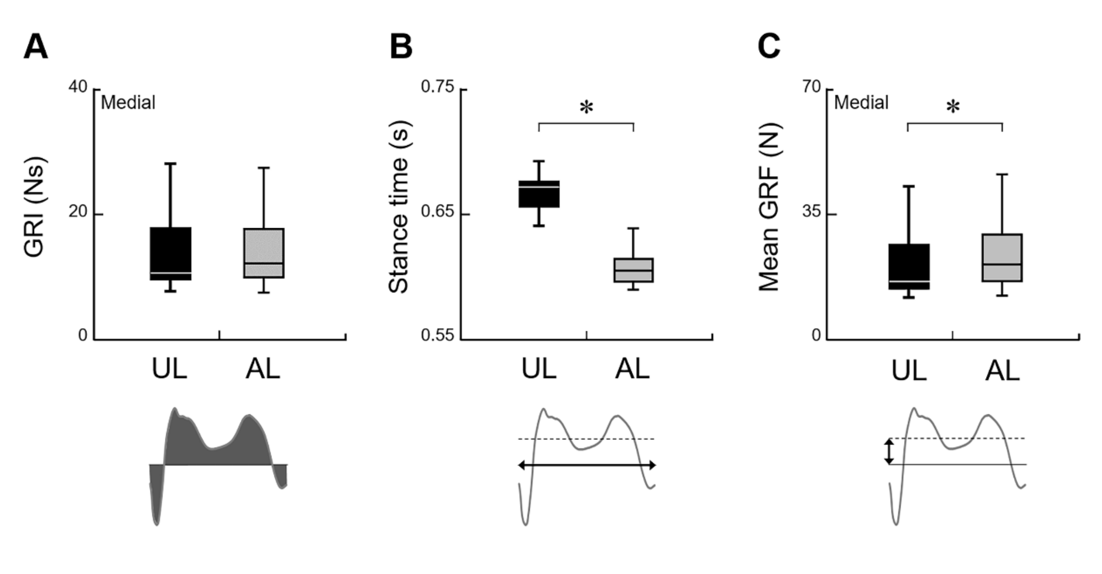
Fig. 1. Mediolateral (A) ground reaction impulse (GRI), (B) stance time, and (C) mean ground reaction force (GRF) of unaffected limb (UL) and affected limb (AL) during straight-ahead walking. An asterisk (*) and horizontal bars indicate significant differences ($p < 0.05$) between the two limbs. At the bottom, the shaded areas depict regions of integrated mediolateral GRF (A). The double-headed arrows indicate the duration (B) and magnitude (C) of mean mediolateral GRF.

Fig. 2. (A) Mean mediolateral ground reaction force (GRF) of affected (dashed line) and unaffected (solid line) limbs during stance phase of straight-ahead walking across 15 individuals with unilateral above-knee (UAK) amputation. The shaded area indicates the standard deviations. Positive values indicate medial GRF components. (B) Associated statistical parametric mapping (SPM) *t*-test results for differences between the curves in (A). The shaded area indicates suprathreshold clusters, which correspond to statistically significant differences between the curves at those nodes (percentage of stance time).

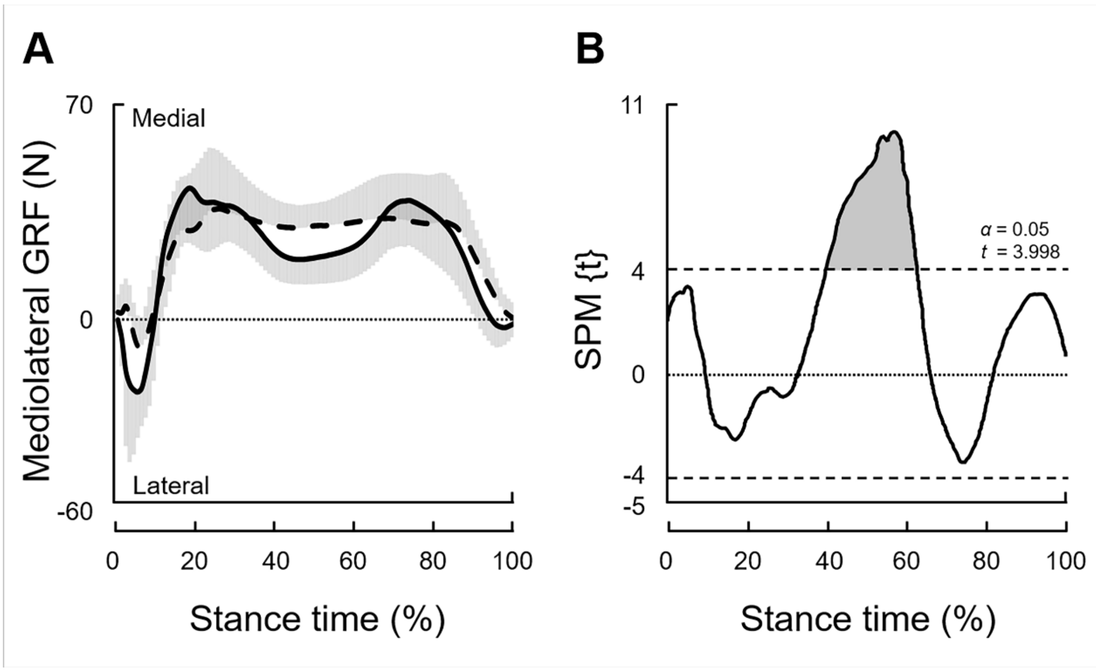
Table 1. Characteristics of individuals with unilateral above-knee (UAK) amputation enrolled in this study. The median is reported together with the 25th and 75th quartiles and interquartile range (IQR). (F: female, M: male, R: right, L: left, AK: Above-knee,

KD: knee disarticulation)

Participant	Gender	Age (years)	Height (m)	Mass (kg)	Amputated side	Etiology	Time since amputation (years)	Residual limb length	Prosthetic knee	Prosthetic foot
1	F	34	1.65	50	R	Cancer	21	Middle TF	3R60	Total concept
2	M	24	1.76	63.0	L	Trauma	3	Long TF	3R95	Variflex
3	M	40	1.67	57.1	L	Cancer	4	Long TF	3R106	Triton
4	M	52	1.7	66.6	L	Trauma	29	KD	4-bar intelligent knee	Lapoc J-foot
5	M	44	1.79	63.6	R	Trauma	28	Short TF	3R80	Triton
6	F	38	1.49	43.9	R	Infection	15	Long TF	4-bar intelligent knee	Total concept
7	M	21	1.67	56.4	L	Cancer	18	Short TF	3R80	Variflex
8	M	43	1.68	67.7	L	Trauma	16	Middle TF	3R80	Variflex
9	F	19	1.49	43.3	R	Cancer	8	Short TF	3R106	1H38
10	M	33	1.67	62.0	L	Trauma	16	Long TF	3R95	Lapoc J-foot
11	F	32	1.56	47.4	R	Trauma	7	Middle TF	Total knee	Total concept
12	F	18	1.56	58.3	R	Trauma	4	Middle TF	Total knee	Variflex xc
13	M	32	1.8	84.5	L	Cancer	24	KD	Genium Xtreme	1D35
14	M	26	1.75	67.2	R	Trauma	5	Middle TF	3R80	Reflex rotate
15	M	34	1.61	59.4	L	Cancer	21	Middle TF	3R95	Variflex
Median	—	33	1.67	59.4	—	—	16	—	—	—
25th	—	24	1.56	50.0	—	—	5	—	—	—
75th	—	40	1.75	66.6	—	—	21	—	—	—
IQR	—	16	0.19	16.6	—	—	16	—	—	—



A
40
Medial
20
0
GRI (Ns)
UL
AL
B
0.75
*
0.65
0.55
Stance time (s)
UL
AL
C
70
Medial
*
35
0
Mean GRF (N)
UL
AL



A
B
70
Medial
Mediolateral GRF (N)
0
Lateral
-60
0
20
40
60
80
100
Stance time (%)
11
α = 0.05
t = 3.998
4
SPM {t}
0
-4
-5
0
20
40
60
80
100
Stance time (%)

Supplementary material for 'Unilateral above-knee amputees achieve symmetric mediolateral ground reaction impulse in walking using an asymmetric gait strategy'

Participant	Step width (m)	Walking speed (m/s)	Standard deviation of Walking speed (m/s)	Peak Medial GRF (N)		Peak Lateral GRF (N)		Standard deviation of GRI (Ns)		Standard deviation of Stance time (s)		Standard deviation of Mean GRF (N)	
				AL	UL	AL	UL	AL	UL	AL	UL	AL	UL
1	0.10	1.21	0.01	34.6	41.1	23.3	31.4	0.8	1.3	0.01	0.01	1.2	1.8
2	0.08	1.36	0.03	35.2	61.6	17.5	107.0	1.7	0.6	0.01	0.01	2.7	1.0
3	0.09	1.52	0.03	40.3	46.2	22.2	17.7	2.2	3.8	0.00	0.00	3.9	5.7
4	0.09	1.38	0.03	61.5	51.3	16.3	12.7	1.0	1.7	0.01	0.00	1.5	2.3
5	0.09	1.43	0.03	41.7	63.6	32.6	35.6	1.5	1.1	0.02	0.01	3.0	1.8
6	0.10	1.20	0.06	27.6	29.0	17.2	13.7	0.8	1.3	0.01	0.01	1.4	1.9
7	0.07	1.36	0.03	35.6	42.4	16.8	50.3	2.4	3.0	0.02	0.01	4.0	4.3
8	0.15	1.32	0.02	82.9	75.4	11.0	56.7	0.9	0.7	0.00	0.02	1.7	1.3
9	0.11	1.20	0.02	20.7	40.4	12.3	28.5	1.7	2.4	0.02	0.01	3.0	3.6
10	0.08	1.22	0.02	32.9	39.7	9.7	39.8	2.0	2.1	0.01	0.01	3.4	3.0
11	0.11	1.25	0.01	28.0	40.2	13.4	12.7	1.5	0.6	0.00	0.01	2.3	1.1
12	0.16	1.18	0.01	36.1	46.7	9.6	13.1	2.9	2.0	0.01	0.01	4.6	3.0
13	0.13	1.41	0.03	73.0	84.7	13.7	28.4	3.6	2.6	0.02	0.02	6.6	4.1
14	0.11	1.80	0.03	41.6	71.1	27.4	41.4	2.3	1.2	0.02	0.01	3.7	1.8
15	0.16	1.46	0.03	67.2	65.5	3.5	19.9	0.7	1.0	0.01	0.01	1.6	1.7
Median	0.10	1.36	0.03	36.1	46.7	16.3	28.5	1.7	1.3	0.01	0.01	3.0	1.9
25th	0.09	1.21	0.02	32.9	40.4	11.0	13.7	0.9	1.0	0.01	0.01	1.6	1.7
75th	0.13	1.43	0.03	61.5	65.5	22.2	41.4	2.3	2.4	0.02	0.01	3.9	3.6
IQR	0.04	0.22	0.02	28.6	25.1	11.2	27.7	1.3	1.4	0.01	0.00	2.3	1.9

Marker placements and data collection

In the present study, prior to the beginning of experiment, the sacral and heel markers were attached to the participants based on Helen Hayes marker set.
The marker position was recorded at 200 Hz using a 3D motion capture system (VICON MX system, VICON Motion System, Oxford, UK) with 15 cameras.
Raw marker data were filtered using a 4th order low pass Butterworth filter with a cut-off frequency of 10 Hz.

Step width and walking speed calculation

Step width was calculated as the mediolateral heel marker's distance between affected and unaffected limb at the initial contact.
Walking speed was calculated as the distance divided by the elapsed time that the sacral marker passed over the nine force plates.

Supplementary material for 'Unilateral above-knee amputees achieve symmetric mediolateral ground reaction impulse in walking using an asymmetric gait strategy'

Participant	Average distance over stance phase (mm)		Distance at peak medial GRF (mm)		Distance at initial contact (mm)	
	AL – COM	**UL – COM**	**AL – COM**	**UL – COM**	**AL – COM**	**UL – COM**
1	—	—	—	—	—	—
2	59.9	17.7	56.2	25.2	77.3	19.5
3	42.2	47.6	49.8	50.0	68.8	56.4
4	46.6	42.8	56.4	42.6	75.1	56.4
5	48.5	41.1	31.7	49.0	75.3	58.4
6	52.0	41.6	53.0	45.7	66.9	55.8
7	30.4	46.3	22.9	37.4	49.9	38.5
8	93.2	53.8	103.8	57.7	151.3	74.9
9	59.5	43.3	54.0	43.6	63.0	47.3
10	36.7	40.5	30.6	40.7	50.4	53.5
11	29.9	57.6	25.7	56.7	39.2	70.3
12	60.6	73.6	51.7	74.1	64.2	91.8
13	50.4	66.6	47.0	57.3	63.4	77.2
14	36.8	56.8	35.6	58.3	44.4	57.6
15	70.4	70.2	75.7	73.7	104.3	90.6
Median	49.4	47.0	50.8	49.5	65.6	57.0
25th	36.8	41.5	31.4	42.1	50.3	51.9
75th	60.1	59.8	56.3	57.9	75.8	75.5
IQR	23.3	18.3	24.8	15.8	25.5	23.5
Wilcoxon signed rank test	p = 0.861 (z = -0.175)		p = 0.575 (z = -0.560)		p = 0.330 (z = -0.974)	

Calculation of the mediolateral distance between each foot and the body COM

The mediolateral distance was defined as the distance between each foot's heel marker and the body COM.
The body COM was determined by the same kinetic and kinematic modelling used in the previous study of our group (Kobayashi et al., 2020).
Since the different marker set was used for subject 1, the position of the body COM was calculated for 14 subjects.
No significant difference was observed in the mediolateral distance between each foot and body COM by the Wilcoxon signed-rank test.

Kobayashi, T., Hisano, G., Namiki, Y., Hashizume, S., Hobara, H., 2020.
Walking characteristics of runners with a transfemoral or knee disarticulation prosthesis. Clinical Biomechanics 80, 105132.